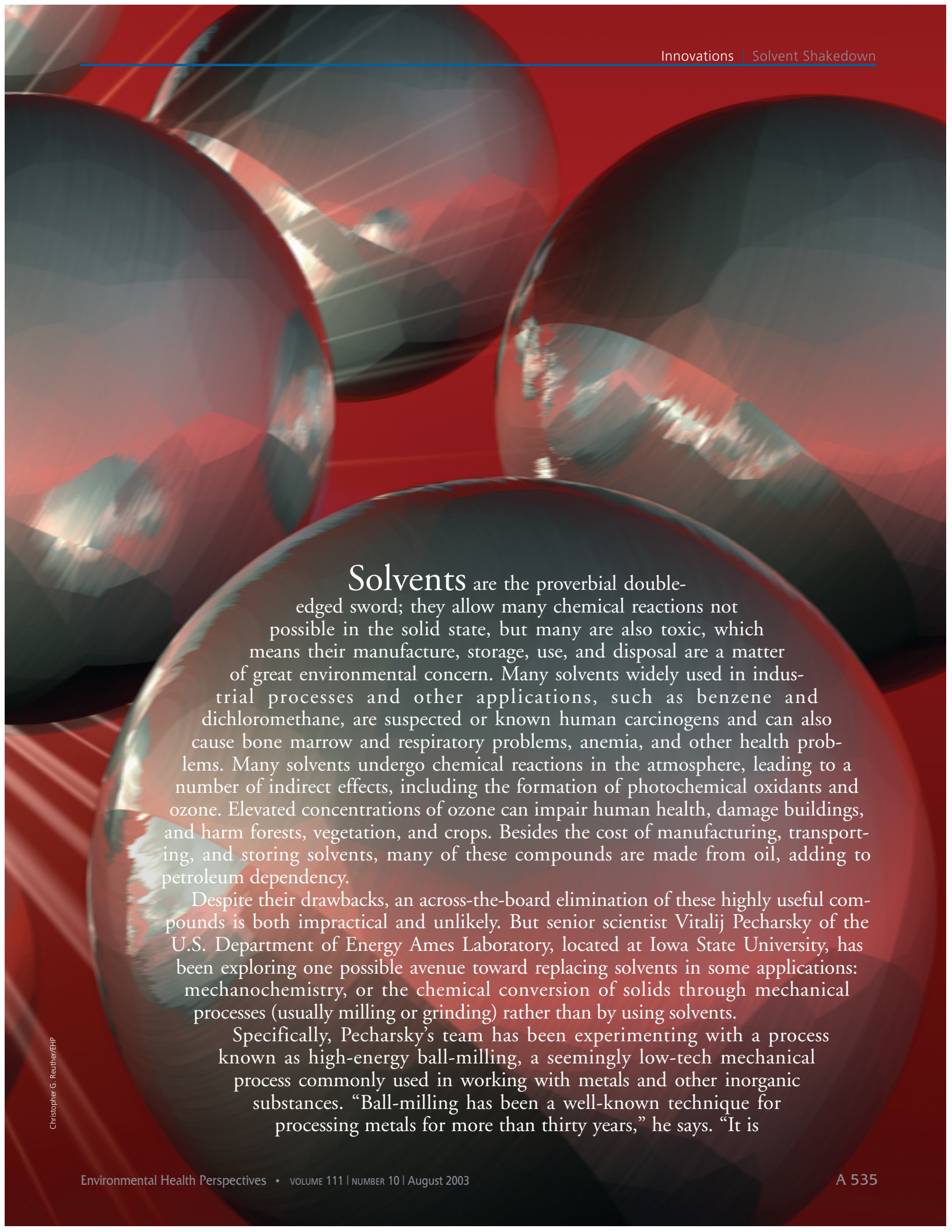


# Solvent Shakedown

The Mechanochemistry Alternative





**Solvents** are the proverbial double-edged sword; they allow many chemical reactions not possible in the solid state, but many are also toxic, which means their manufacture, storage, use, and disposal are a matter of great environmental concern. Many solvents widely used in industrial processes and other applications, such as benzene and dichloromethane, are suspected or known human carcinogens and can also cause bone marrow and respiratory problems, anemia, and other health problems. Many solvents undergo chemical reactions in the atmosphere, leading to a number of indirect effects, including the formation of photochemical oxidants and ozone. Elevated concentrations of ozone can impair human health, damage buildings, and harm forests, vegetation, and crops. Besides the cost of manufacturing, transporting, and storing solvents, many of these compounds are made from oil, adding to petroleum dependency.

Despite their drawbacks, an across-the-board elimination of these highly useful compounds is both impractical and unlikely. But senior scientist Vitalij Pecharsky of the U.S. Department of Energy Ames Laboratory, located at Iowa State University, has been exploring one possible avenue toward replacing solvents in some applications: mechanochemistry, or the chemical conversion of solids through mechanical processes (usually milling or grinding) rather than by using solvents.

Specifically, Pecharsky's team has been experimenting with a process known as high-energy ball-milling, a seemingly low-tech mechanical process commonly used in working with metals and other inorganic substances. "Ball-milling has been a well-known technique for processing metals for more than thirty years," he says. "It is



also used to process a variety of inorganics, because the forces used result in considerable microstructural changes.”

In its simplest terms, ball-milling involves sealing ingredients in a hardened steel container along with a number of heavy metal balls, and then shaking or vibrating the container. The balls crash about, impacting each other, the container walls, and the materials inside. The random, chaotic motion of the heavy agitation creates tremendous numbers of collisions, imparting a great deal of energy and breaking existing bonds to allow for the formation of new bonds. When the container is opened, the ingredients have been transformed into an end product without the use of any additional chemicals.

“It is a bit of a surprise, I suppose, that you can get much the same results with steel balls as you can with solvents,” says Laszlo Takacs, an associate professor of physics at the University of Maryland, Baltimore County. “And I suppose it’s even more of a surprise that you might be able to do the same thing with organic materials [because of the strength of their bonds]. But until the end of the nineteenth century, people didn’t believe that

you could initiate chemical reactions by mechanical means. This is all relatively new knowledge.”

It’s knowledge that may be coming just in time, however. “One of the goals of green chemistry is the reduction of the use of solvents,” says American Chemical Society chemist Sam Stevenson—if solvents can’t be eliminated, then at least the volume used should be reduced. “You’d save on the cost to manufacture, store, use, and recapture,” he says, “and you’d reduce the impact on the environment and on the people in the industry using the solvents. For environmental purposes, you’d especially like to reduce the volume of organic solvents.”

### Rolling Out a New Use for Ball-Milling

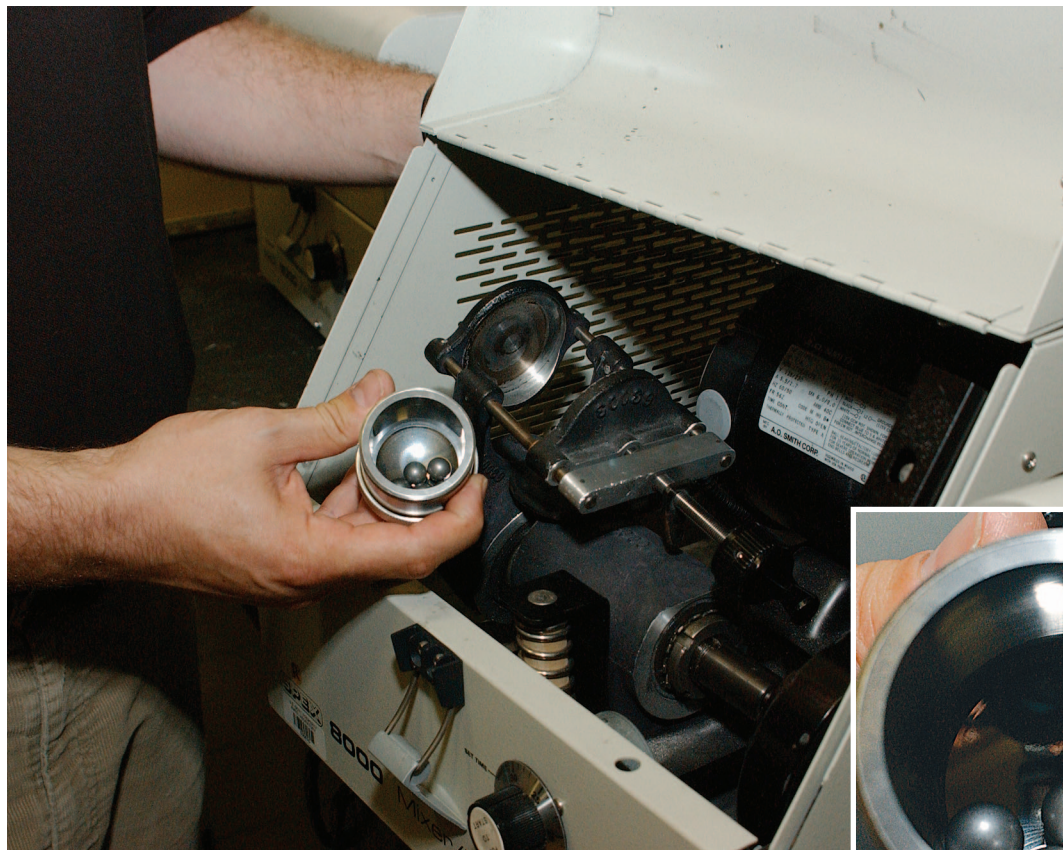
According to Pecharsky, the molecules of organic compounds are bound to one another by relatively weak hydrogen bonds and a connectivity known as the van der Waals force. These weak bonds are easily broken by organic solvents, such as benzene, freeing up sites for new molecular bonds to form and thus create new molecular compounds. “Solvents can also

provide a transfer medium in which different molecules continuously move about,” he says. “In some cases,” he adds, “solvents also participate in the chemical reaction.”

As Pecharsky discovered, the same effect can be achieved by high-energy ball-milling. In one experiment, described in volume 124, issue 22 (2002) of the *Journal of the American Chemical Society*, he and his colleagues generated compounds known as phosphorus ylides (or phosphoranes) without solvents, the first time such a feat had been reported. They used an SPEX 8000 series mixer/mill, a commercially available ball-mill made by the Metuchen, New Jersey-based company SPEX CertiPrep. The mill is capable of agitating two containers in a back-and-forth pattern several thousand times per minute. The vials, which are about two inches wide and up to three inches long, are made in a variety of materials, including hardened steel, tungsten carbide, and methacrylate, and can hold approximately 20 grams of small hardened metal balls and about 10 grams of material to be processed. Commercial-scale mills capable of processing hundreds of pounds of

material also are available, says Pecharsky.

The team created the ylide (benzoylmethylene)triphenylphosphorane by ball-milling (phenacyl)triphenylphosphonium bromide with anhydrous potassium carbonate ( $K_2CO_3$ ), a base. They created (carbethoxymethylene)triphenylphosphorane by ball-milling (carbethoxymethyl)triphenylphosphonium bromide with  $K_2CO_3$ . The finished products were analyzed by X-ray diffraction, differential



**Low-tech chemistry with a high payoff.** High-energy ball-milling, a relatively low-tech process in which metal balls are sealed in a vial with chemicals and shaken to produce new substances, may replace solvents in certain chemical reactions, offering at least a partial alternative to the use of toxic compounds such as benzene.



thermal analysis, and solid-state nuclear magnetic resonance. These and several other compounds created were found to be of a purity comparable to those prepared using solvents. Examination six months after ball-milling showed no evidence of solid-state thermal reactions; the compounds produced without solvents were stable.

Pecharsky points out another intriguing difference between conventional solvent-based ylide generation and ball-milling: the bases required for each process. A base is any chemical species capable of accepting a proton (hydrogen ion) from another substance. The greater the tendency to accept a proton, the stronger the base. The base acts as a catalyst to remove hydrogen ions and bind protons, allowing the formation of new compounds. Solvents must be used in the presence of a strong base such as lithium-based compounds (lithium is a suspected kidney toxicant and neurotoxicant). Although ball-milling also requires a base catalyst, the physics of the technology allows the use of a much milder base— $K_2CO_3$ .

In this experiment, ball-milling showed a further advantage beyond eliminating toxic components: it was carried out as what Pecharsky and colleagues called a straightforward “one-pot” process, with ingredients that normally must be combined in stages being more efficiently combined all at once in the ball-mill.

### Questions Milling About

One concern that must be addressed when dealing with organic material is the issue of heat buildup. “Solvents, in addition to their other roles, serve as heat sinks,” says Nhan Nguyen, chief of the EPA Chemical Engineering Branch. “I expect that this kind of technology may generate a lot of heat [when used with organics], and it doesn’t have to get too hot before organic material starts breaking down. This technology may also be harder to control in terms of product

[characteristics] than those using solvents, in which the kinetics are better understood.”

That’s a good point, agrees Tracy Williamson, chief of the EPA Industrial Chemistry Branch. “As an example,” he says, “in some solventless polymer manufacturing processes, heat generated isn’t easily removed. Initially, some products made with grinding processes had some negative characteristics—specifically discoloration of the polymer caused by heat buildup—that made them noncompetitive.”

He further explains that organic materials aren’t as robust as metals. In metals, heat can create some melting, which can actually help with mixing, but organics can’t take too much heat before they start to decompose.

According to Pecharsky, at least one experiment was run with a simple fan providing cooling to prevent organic decomposition, and Takacs adds that most large-scale ball-mills have some sort of cooling mechanism. Pecharsky says, “In my mind, [heating] is not a problem, and certainly not for all ball-milling of organics.”

It’s an intriguing technology, admits Williamson, but he is concerned about what happens further downstream, when ball-milling has to be scaled up to meet commercial demands, and what steps industry will have to take to apply this technology. “A lot of wonderful technology is never applied because of scale-up issues and other problems,” he says.

Other concerns surround the by-products that ball-milling, like most manufacturing processes, may produce. These by-products can compromise the purity of the target product. “It seems likely,” says Williamson, “that this technology would produce mixtures that may require a solvent-based separation step to isolate the desired product. The increased energy demands may also outweigh the benefits from getting rid of the solvent.”

A similar purity concern is raised by Terry Fay, a principal process engineer

for Lockwood Greene, a Spartanburg, South Carolina-based engineering and construction firm. “We don’t typically break molecules apart mechanically because it takes a lot of energy, and it’s much easier to do with a solvent,” he says. “If you have a system where you can put in that much energy, my question is then how do you know you’re breaking the bonds at the right place? There seems to be a certain inherent randomness to this process, and if the molecule you’re dealing with doesn’t break at the right place, then you have a by-product, which has to be treated as waste. I don’t see how the process can be very selective.” To this, Pecharsky responds that reactions in solvents are also governed by random processes as molecules move about in a random fashion. “The selectivity of the mechanochemical process is an experimentally established fact in several instances, as described in our papers [see Suggested Reading, below],” he says.

Despite the questions still surrounding the technique, Pecharsky believes the advantages of this system will be manifold. Although he agrees it’s unlikely that solvent usage will ever be eliminated for all processes, he says it’s possible that ball-milling will allow for the use of more benign solvents, such as supercritical carbon dioxide or even water, for many processes. And because structural changes and chemical reactions are induced by mechanical rather than thermal energy, ball-milling systems may have lower energy input requirements, although more research is needed before this can be verified.

“Additionally,” he says, “our experiments showed that phosphoranes, which are used as precursors in the synthesis of a variety of saturated and unsaturated hydrocarbons, can be created this way, and in what would be a one-step process. That is more economical [than current processes, which involve several steps and repeated purification], and it avoids having to purify any of the intermediate products.”

A provisional patent has been filed for ball-milling of organic compounds, but mechanochemistry, Pecharsky says, is not a magic wand. “You can’t just eliminate solvents, because mechanochemistry isn’t suitable for all processes,” he says. “But this is just the tip of the iceberg. Others will discover new processes, new reactions, and I think a few years down the road, we’ll see a number of products made by solvent-free processes.”

Lance Frazer

### Suggested Reading

Balema VP, Wiench JW, Pruski M, Pecharsky VK. 2002. Mechanically induced solid-state generation of phosphorus ylides and the solvent-free Wittig reaction. *J Am Chem Soc* 124:6244–6245.

Balema VP, Wiench JW, Pruski M, Pecharsky VK. 2002. Solvent-free mechanochemical synthesis of phosphonium salts. *Chem Commun* 2002(7):724–725.

Balema VP, Wiench JW, Pruski M, Pecharsky VK. 2002. Solvent-free mechanochemical synthesis of two Pt complexes: *cis*-( $Ph_3P$ )<sub>2</sub>PtCl<sub>2</sub> and *cis*-( $Ph_3P$ )<sub>2</sub>PtCO<sub>3</sub>. *Chem Commun* 2002(15):1606–1607.